Quasar viscosity crisis

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Recent observations of extreme variability in active galactic nuclei have pushed standard viscous accretion disk models over the edge. I suggest either that some kind of non-local physics dominates accretion disks, or that the optical output we see comes entirely from reprocessing a central source.

Andy Lawrence

It is widely believed that active galactic nuclei (AGN), including the most luminous examples, quasars, are powered by accretion disks surrounding supermassive black holes. We have understood the general principles of accretion disks since the 1970s[1–3]. The disk rotates differentially, so neighbouring rings slip past each other. Some viscous process causes a drag between the rings, thereby transferring angular momentum outwards and producing local heating. If that local heating is also radiated thermally on the spot, this process determines the radial temperature profile ($T \propto R^{-3/4}$). A further simplifying assumption — that viscosity is proportional to the speed of sound — allows a complete solution of the disk structure. A well-known problem is that standard molecular viscosity, whereby particles from the fast lane slip into the slow lane and vice versa, is far too weak to explain the observed luminosities. From the 1970s onwards it was widely assumed that some of kind of turbulence and/or magnetic stresses would produce a viscosity-like effect. This idea was put on a sound footing in 1991, with the development of the theory of magneto-rotational instability (MRI)[4].

Accretion disk models nicely explain the luminosity and compactness of AGN, as well as the observed peak of the spectral energy distribution in the ultraviolet (UV) regime. Getting the details right has always been difficult[5], but these problems may be explained by effects that modify the spectral energy distribution, such as the presence of a Comptonizing atmosphere, or a system of clouds surrounding the disk[5,6]. However, by far the worst problem is variability. AGN vary significantly on timescales of weeks to months, whereas disks with the right degree of viscosity to explain the luminosity should take thousands of years to change their optical emission. Furthermore, variations at different wavelengths, from the optical through to the UV, vary simultaneously and have aligned peaks[7] (Fig. 1a), whereas in an accretion disk, different wavelengths come from different radii, which means changes should propagate through the disk.

This situation was rescued in the 1990s with the idea of X-ray reprocessing[8], whereby the central X-ray source, which can vary much more quickly than the part of the disk generating the optical light, shines on the disk and heats it. At any radius, heating has two causes: viscous heating, which changes only slowly; and X-ray heating, which can change quickly. Noticeably, although the shortest UV wavelengths might change by (say) a factor of two peak-to-trough, the redder optical wavelengths change only by a few per cent. There have been many papers arguing about whether or not X-ray reprocessing works in detail. The strongest argument in favour is the observation of delays between the variations at different wavelengths — on a timescale of hours to days, which is consistent with the travel-time delays of light[9,10].

However, the variability problem is now reaching a new crisis, thanks to the observation of extreme variability in some objects — factors of several over a decade or so, including, crucially, at optical wavelengths, not just in the extreme UV or X-ray regimes. Large changes have been known in a handful of nearby low-luminosity AGN for many years, but data comparison between the Sloan Digital Sky Survey and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) has revealed a large number of such objects[11] (Fig. 1b), including many at high luminosity. These objects have generally been referred to as 'changing-look quasars'. The broad emission lines that normally accompany type I (that is, quasar-like) AGN seem to come and go along with the optical continuum; when the continuum and broad lines plummet, what is left behind is the narrow emission lines that dominate type II AGN. The varying broad emission lines tell us that the far-UV, as well as the optical emission must be changing dramatically.

Because these large changes occur in optical emission — not only in X-ray or far-UV emission — it seems difficult to avoid the conclusion that the outer region of the disk itself is undergoing a gross physical change on a timescale inconsistent with viscous heating. Furthermore, recent work, such as that comparing the Dark Energy Survey and the Sloan Digital Sky Survey, seems to suggest that extreme variability is not that unusual — possibly 30–50% of quasars sometimes vary by a large amount[12]. Studies of the variability structure function also suggest that the degree of optical variability for a typical quasar climbs inexorably at longer timescales[13]. Although some AGN have larger typical variability than others on any given timescale, it seems likely that all AGN vary dramatically if you wait long enough.

One might wonder whether some kind of variable obscuration, such as passing clouds in the clumpy torus, can explain the variability. However, studies of large changes usually conclude that this idea doesn't fit the observations, because the timescales, the (lack of) colour changes and the relative line and continuum changes look wrong (Fig. 1b). It seems we really must confront the fact that accretion disk models are failing. Of course, good theorists have long-known that standard viscous accretion disk theory is just too simple, but it remains the observers' paradigm. When interpreting data, researchers routinely assume that the standard theory is correct, and write optimistically of 'accretion disk instabilities' to explain outbursts. The problem is that the existence of common large-amplitude variability suggests that disks are in a state of permanent exception; it is not reasonable to describe them with standard viscous accretion disks at all. As Pringle said in 1981[14], 'instability' really means 'inconsistency'.

We cannot solve this problem by simply cranking up the viscosity parameter. The rate of torque is closely related to the viscous scale length and therefore to the disk height, so the disk approximation breaks down completely. What can be done?

Non-local processes

Perhaps we must abandon the hope that the transfer of angular momentum, the

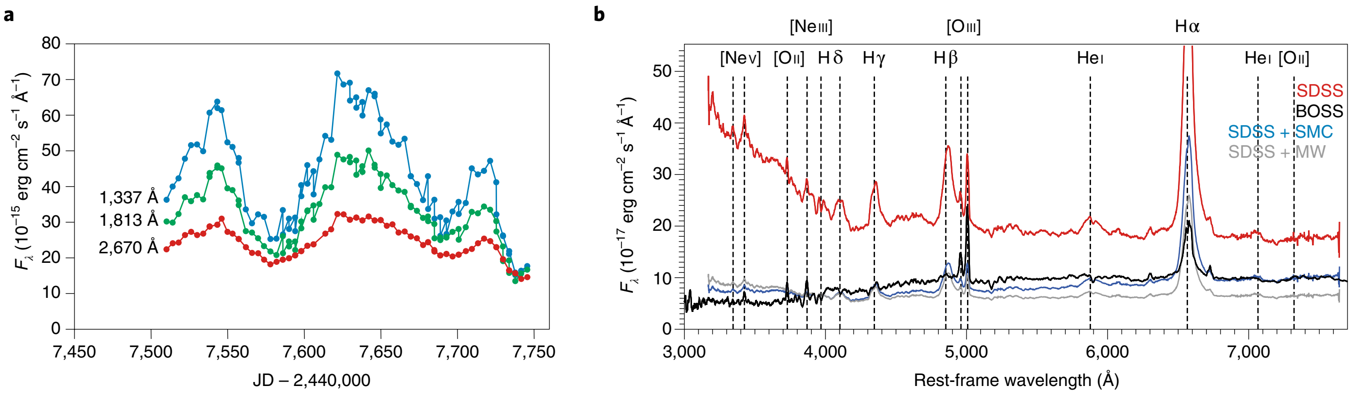

Fig. 1 | Extreme variability in AGN. a, Variations in the near-UV brightness (flux per unit wavelength, F_λ) in NGC 5548 at three different wavelengths, showing the short timescale, the simultaneity at different wavelengths, and the differing amplitude at different wavelengths, all three of which are serious problems for the standard viscous disk theory. The data points were taken from the International AGN Watch. **b**, A dramatic change over a period of years in the quasar J1021+1645. In the lower part of the plot, the black curve is the data. The blue and grey curves are (failed) attempts to model the collapse by a change in extinction. Credit: Panel **b** reproduced from ref. [11], Oxford Univ. Press.

generation of heat and the radiation of that heat can all be approximated as local and co-located processes. Large-scale magnetic fields can cause one ring to drag on a very distant ring, corkscrew-like outflows can carry angular momentum away, and, if infall on a dynamical timescale is possible, heating and radiation may be only loosely coupled to gravitational energy generation. All these ideas have the smell of physical realism. Much of the basic physics has been laid out[15], and there are some real models for stellar-scale black-hole systems[16]. The trouble is that there are many such ideas, and most of them sound horribly difficult to work out in detail; what would we expect the spectral energy distribution to look like?

Cold disk reprocessing

The light-travel time delays in some objects, together with the fact that variations seem to be on something like a thermal timescale, strongly suggest that at least some of the optical emission is reprocessed — therefore why not all of it? Perhaps the bulk of the disk has small viscosity, and is massive, cold and has a low accretion rate. At some small radius (perhaps 3–10 R_S, where R_S is the Schwarzschild radius) conditions change and rapid accretion occurs, whereby material peels off the inner radius of the cold disk and plunges towards the black hole. Or perhaps the spin-energy of the black hole is extracted by the Blandford–Znajek process. One way or another, this inner region is where nearly all of the energy is generated, but a large fraction of this energy heats the otherwise cold outer disk. To solve the known problems with existing models, it is very likely that reprocessing occurs not in the disk itself, but in clouds lifted out of the disk. The response of the disk to erratic variations of the central source will be subtle, having both a prompt response (skin heating and scattering) and a smooth response (deep heating from the history of the central source luminosity). It could be that the main role of the disk is to generate reprocessing clumps — all the way from the inner disk at 10 R_S out to the traditional broad line region at 1,000 R_S. ❐

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